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Analysis of the exclusive semileptonic decay $\Lambda_b \to \Lambda_c + \ell \bar{\nu}_\ell$ within a light-front constituent quark model[a]

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Abstract

The exclusive semileptonic decay $\Lambda_b \to \Lambda_c + \ell \bar{\nu}_\ell$ is investigated including both radiative and first-order power corrections in the inverse heavy-quark mass, while the Isgur-Wise function is calculated within a light-front constituent quark model. It turns out that the dependence on the model parameters can be effectively constrained using recent lattice QCD results at low values of the recoil. Our final predictions for the exclusive semileptonic branching ratio, the longitudinal and transverse asymmetries, and the longitudinal to transverse decay ratio are: $Br(\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell) = (6.3 \pm 1.6)\ \%\ |V_{bc}/0.040|^2\ \tau(\Lambda_b)/(1.24\ ps)$, $a_L = -0.945 \pm 0.014$, $a_T = -0.62 \pm 0.09$ and $R_{L/T} = 1.57 \pm 0.15$, respectively. Moreover, the theoretical uncertainties both on a_L and the (partially integrated) $R_{L/T}$ are found to be quite small and, therefore, the experimental determination of these quantities is a very interesting tool for testing the Standard Model and for investigating possible New Physics. In this respect the sensitivity to extract unique information both on the strength and phase of possible hadronic right-handed currents is illustrated.

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1 INTRODUCTION

The investigation of the exclusive semileptonic decays of heavy hadrons, driven by the elementary process $b \to c + \ell \bar{\nu}_\ell$, can provide relevant information on fundamental parameters of the Standard Model (SM), like e.g. the quark masses and the weak mixing angle $V_b c$, as well as on possible extensions of the SM. In this contribution we present the main results of an analysis of the decay $\Lambda_b \to \Lambda_c + \ell \bar{\nu}_\ell$ performed recently in Refs. [1, 2] adopting a relativistic quark model formulated on the light-front, and we illustrate also the possibility to extract relevant information on hadronic right-handed currents from the $\Lambda_b \to \Lambda_c + \ell \bar{\nu}_\ell$ process.

In Refs. [1, 2] the Isgur-Wise (IW) form factor relevant for the $\Lambda_b \to \Lambda_c + \ell \bar{\nu}_\ell$ decay has been calculated in the whole accessible kinematical range adopting a light-front constituent quark model and using various forms of the three-quark wave function. It turns out that the IW form factor is sensitive to relativistic delocalization effects associated to the light-quark degrees of freedom, leading to a saturation property of the IW form factor as a function of the canonical baryon size. Moreover, the shape of the IW function is found to be significantly affected by the baryon structure, being sharply different in case of diquark-like or collinear-type configurations. The comparison with recent lattice QCD calculations [3] as well as with the (model-dependent) dispersive bounds of Ref. [4] suggests clearly the dominance of collinear-type configurations with respect to diquark-like ones, and allows to put effective *constraints* on the shape of the IW function in the full recoil range relevant for the $\Lambda_b \to \Lambda_c + \ell \bar{\nu}_\ell$ decay (see Ref. [2] for more details).

2 ANALYSIS OF THE $\Lambda_b \to \Lambda_c + \ell \bar{\nu}_\ell$ DECAY WITHIN THE SM

The $\Lambda_b \to \Lambda_c + \ell \bar{\nu}_\ell$ decay has been investigated within the framework of the SM including radiative as well as first-order $1/m_Q$ corrections to the relevant form factors, as derived in Ref. [5]. Our final predictions for the exclusive semileptonic branching ratio, the longitudinal and transverse asymmetries, and the longitudinal to transverse decay ratio are: $Br_{SL} = (6.3 \pm 1.4)\ \%\ |V_{bc}/0.040|^2\ \tau(\Lambda_b)/(1.24\ ps)$, $a_L = -0.94 \pm 0.01$, $a_T = -0.62 \pm 0.08$ and $R_{L/T} = 1.57 \pm 0.12$, respectively. Our results for the partially-integrated exclusive semileptonic branching ratio are reported in Fig. 1 and compared with the corresponding results from the lattice QCD simulations of Ref. [3]. It can be seen that our results are always well within the range of values given by the lattice QCD simulations and that radiative plus first-order power corrections modify only slightly the results obtained within the Heavy Quark Symmetry (HQS). If the integration over the recoil is limited to $\omega = 1.2$, then the resulting uncertainty on the branching ratio reduces significantly to $\simeq 12\%$, though at the price of reducing the number of the events by a factor $\simeq 0.44$ (see Table 2 of Ref. [2]). This implies the possibility to extract the CKM matrix elements $|V_{bc}|$ with a theoretical uncertainty of $\simeq 6\%$, which is comparable with present uncertainties obtained from exclusive semileptonic B-meson decays [7].

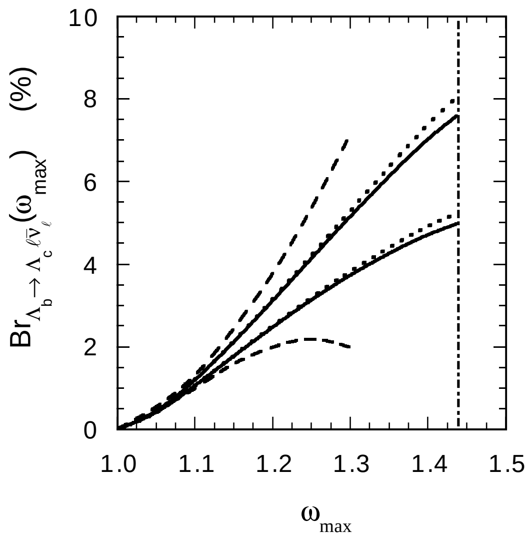

Figure 1. Partially-integrated branching ratio $Br_{\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell}(\omega_{max})$ in % versus the upper limit of integration over the recoil, ω_{max}, calculated at $|V_{bc}| = 0.040$ and $\tau(\Lambda_b) = 1.24\ ps$ [6]. The solid and dashed lines correspond to our and lattice QCD results [3], respectively. The lower and upper solid lines are the results corresponding to the lower and upper limits of the IW function derived in Ref. [2], including radiative plus first-order $1/m_Q$ corrections. The dotted lines are the HQS results. The vertical dot-dashed line indicates the physical threshold $\omega_{th} \simeq 1.44$. (After Ref. [2]).

In Ref. [2] various partially-integrated asymmetries have been investigated, showing that in comparing with (future) data the precise ω-range of the experiments has to be taken into account. It turns out that radiative plus first-order $1/m_Q$ corrections are relevant for the transverse asymmetry a_T and for the longitudinal Λ_c polarization P_L, whereas both a_L and $R_{L/T}$ are only marginally affected by such HQS corrections, as it is clearly shown in Fig. 2. Moreover, the model dependence on the various asymmetries is generally quite limited and, in particular, our uncertainty on $R_{L/T}$, which is always much less than the one presently achievable by lattice QCD calculations, reduces to $\simeq 1\%$ when the integration over the recoil is limited to $\omega = 1.2$.

3 EFFECTS FROM POSSIBLE RIGHT-HANDED CURRENTS

The small uncertainties found for the longitudinal asymmetry a_L and the longitudinal to transverse decay ratio $R_{L/T}$ make the experimental determination of these quantities a very interesting tool for testing the SM and investigating possible New Physics (NP). We now illustrate the sensitivity of a_L and $R_{L/T}$ to the introduction of possible hadronic right-handed currents by considering the presence in the effective weak Hamiltonian of both left-handed (LH) and right-handed (RH) operators, viz. $\mathcal{H}_{eff}(b \to c\ell\bar{\nu}_\ell) = c_L O_L(b \to c\ell\bar{\nu}_\ell) + c_R O_R(b \to c\ell\bar{\nu}_\ell)$, where $O_{L(R)}(b \to c\ell\bar{\nu}_\ell) \equiv (\bar{c}\gamma_\mu(1 \mp \gamma_5)b)(\ell\gamma^\mu(1-\gamma_5)\nu_\ell)$, with the values of the coefficients c_L and c_R depending on the specific NP model. In general $c_L \neq c_L^{(SM)}$, but in what follows we consider for simplicity $c_L = c_L^{(SM)}$, and we introduce two parameters, ρ and η, defined as $\rho \equiv |c_R|/|c_L|$ and $\eta \equiv -\mathrm{Re}(c_L c_R^*)/(|c_L|^2 + |c_R|^2)$, which are clearly connected to the relative strength and phase of RH currents with respect to LH ones. On one hand side we have

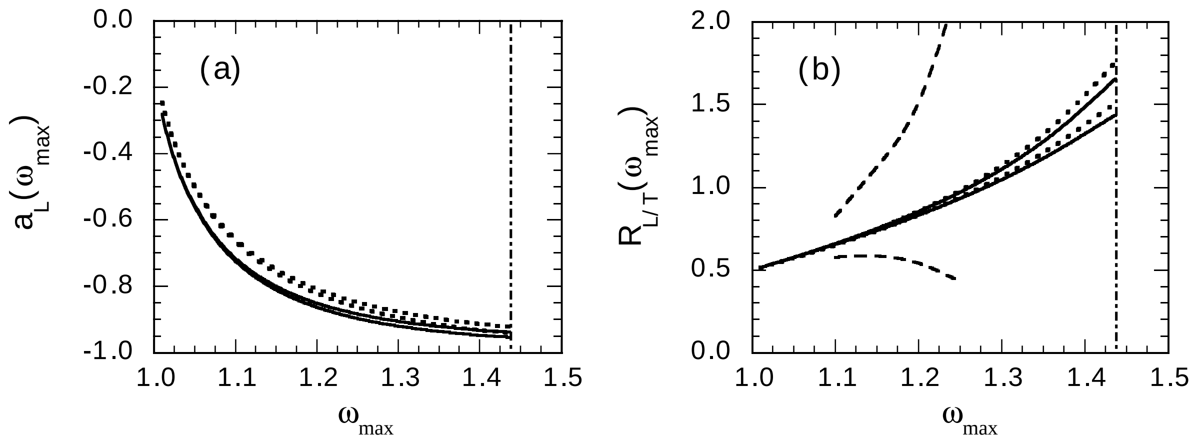

Figure 2. Partially-integrated longitudinal asymmetry a_L (a) and longitudinal to transverse decay ratio $R_{L/T}$ (d) versus the upper limit of integration over the recoil, ω_{max}, for the decay process $\Lambda_b \to \Lambda_c + \ell\bar{\nu}_\ell$. The dotted and solid lines correspond to the HQS results and to those obtained including radiative plus first-order $1/m_Q$ corrections, respectively. The meaning of the lower and upper lines, as well as of the vertical dot-dashed line, is as in Fig. 1. In (b) the dashed lines correspond to the lattice QCD results of Ref. [3]. (Adapted from Ref. [2]).

found that the branching ratio Br_{SL} is sharply sensitive to the values of ρ and η; however, the SM predictions for Br_{SL} (see Fig. 1) can be obtained also with different pairs of values of $(\rho,\ \eta)$. On the other hand side our main results for a_L and $R_{L/T}$ are summarized in Fig. 3. It can be clearly seen that both a_L and $R_{L/T}$ are significantly sensitive to the presence of RH currents, but their determination allows the extraction of information both on the strength and phase of RH currents.

4 CONCLUSIONS

The exclusive semileptonic decay $\Lambda_b \to \Lambda_c + \ell\bar{\nu}_\ell$ has been investigated including both radiative and first-order power corrections in the inverse heavy-quark mass, while the Isgur-Wise function has been calculated within a light-front constituent quark model. The dependence on the model parameters has been effectively constrained using recent lattice QCD results at low values of the recoil. Our predictions for the exclusive semileptonic branching ratio, the longitudinal and transverse asymmetries, and the longitudinal to transverse decay ratio are: $Br(\Lambda_b \to \Lambda_c \ell\bar{\nu}_\ell) = (6.3 \pm 1.6)\ \%\ |V_{bc}/0.040|^2\ \tau(\Lambda_b)/(1.24\ ps)$, $a_L = -0.945 \pm 0.014$, $a_T = -0.62 \pm 0.09$ and $R_{L/T} = 1.57 \pm 0.15$, respectively. Moreover, the theoretical uncertainties both on the longitudinal asymmetry and the (partially integrated) longitudinal to transverse decay ratio are found to be quite small and, therefore, the experimental determination of these quantities is a very interesting tool for testing the Standard Model and for investigating possible New Physics. In this respect the possibility to extract unique information both on the strength and phase of hadronic right-handed currents has been illustrated.

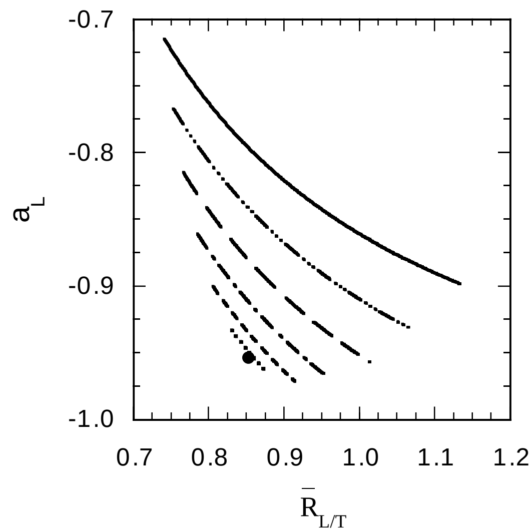

Figure 3. The longitudinal asymmetry a_L versus the partially-integrated longitudinal to transverse ratio $\bar{R}_{L/T} \equiv R_{L/T}(\omega_{max} = 1.2)$ for the decay process $\Lambda_b \to \Lambda_c + \ell\bar{\nu}_\ell$. The full dot corresponds to the results calculated within the SM framework, while the various lines are obtained for fixed values of ρ and varying η in its allowed range (see text). The dotted, dashed, dot-dashed, long-dashed, triple-dotted-dashed and solid lines correspond to $\rho = 0.05, 0.10, 0.15, 0.20, 0.25$ and 0.30, respectively.

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